Closed-loop Control of Functional Neuromuscular Stimulation

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This QPR is being sent to
you before it has been
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Neural Prosthesis Program.

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1. SYNTHESIS OF UPPER EXTREMITY FUNCTION

The overall goals of this project are (1) to measure the biomechanical properties of the neuroprosthesis user's upper extremity and incorporate those measurements into a complete model with robust predictive capability, and (2) to use the predictions of the model to improve the grasp output of the hand neuroprosthesis for individual users.

1. a. BIOMECHANICAL MODELING: PARAMETERIZATION AND VALIDATION

Purpose

In this section of the contract, we will develop methods for obtaining biomechanical data from individual persons. Individualized data will form the basis for model-assisted implementation of upper extremity FNS. Using individualized biomechanical models, specific treatment procedures will be evaluated for individuals The person-specific parameters of interest are tendon moment arms and lines of action, passive moments, and maximum active joint moments. Passive moments will be decomposed into components arising from stiffness inherent to a joint and from passive stretching of muscle-tendon units that cross one or more joints.

Report of progress

1. a. i. MOMENT ARMS VIA MAGNETIC RESONANCE IMAGING

Abstract

In this quarter, we continued to test methods for moment arm measurement from 3D MRI images. We have focused on the reproducibility of the measurement. One experiment consisted of imaging and measuring one subject (RM) two times with a month between image acquisitions. Excellent reproducibility was found with the tendon excursion method. Reproducibility of the 3D geometric method was less good. Also, the agreement between the two methods was not as good as in the case of the measurement on another subject (KJ) reported in the last quarter. We are continuing to modify and investigate the 3D geometric method. Activity in the next quarter will focus on acquiring images and comparing the methods on more subjects.

Progress Report

We are testing methods for measuring tendon moment arm in the MCP joints of the fingers. As described in a previous report, we consider this joint to be simpler than the wrist; hence, we elect to study it first. We use high-resolution, 3D MRI to measure tendon moment arm, and our initial goal is to determine an accurate, practical method. As described in the proposal, we are examining 3 methods for analyzing tendon moment arm. They are: tendon excursion, 3D geometric, and 2D geometric. In previous reports, we detailed the tendon excursion and the 3D geometric method. A new 2D method is not yet complete.

We use a new open-magnet MRI system, and previous reports detailed the imaging methods. A very important aspect is the creation of the hand and wrist holder shown in Figure 1.a.i.1. This holder allows for flexion/ extension of the wrist and fingers. Hinges in the holder are held in place with lock screws. In order to fix the hand in imaging space, there is a connection between the holder and the imaging magnet. A variety of straps provide the firm support to the hand, fingers, and arm necessary for motion free imaging. The creation of this holder was a much larger effort than originally planned.

We repeated imaging experiments on a healthy male subject (RM) without any known hand injury on two different days separated by one month. The results of the tendon excursion method are given in Figure 1.a.i.2. The tendon excursion method is very repeatable with the largest difference being only 9%. The reproducibility of the geometric method is not quite as good with the largest percent difference of 24% (not shown). All data are analyzed by one experienced operator. Using one set of image data, we compared analysis of one experienced operator with one much less experienced. In this inter-observer study, very good agreement was obtained in two of three positions.

Figure 1.a.i.1 This finger and hand holder is used in the measurement of tendon moment arm using 3D MRI. The apparatus has hinges that enable us to hold the fingers and wrist at various flexion/extension angles. Soft straps firmly hold the hand in place. A white, cylindrical imaging coil encircles the wrist.

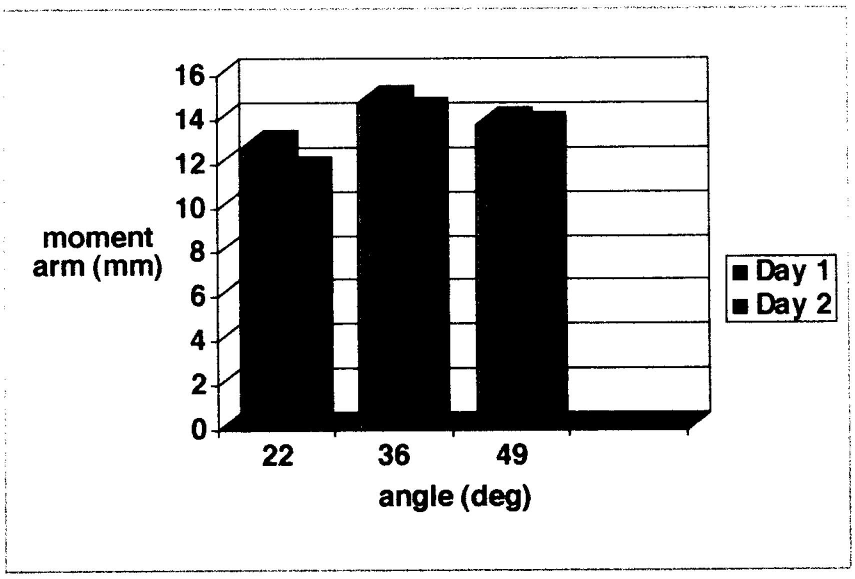

Figure 1.a.i.2 The tendon excursion method is performed on the same subject on two different days separated by more than a month. From four finger positions, the moment arm is measured at three flexion angles. The tendon is the profundus at the 3rd MCP joint.

In both the 3D geometric and tendon excursion methods, the largest differences between day 1 and day 2 were obtained at the greatest flexion of the finger. Images taken in this position have the poorest image quality owing to the distance and off-axis positioning with respect to the imaging coil. The less than optimal image quality probably leads to the inaccuracies in bone segmentation and tendon tracking, and probably explains the differences in tendon moment arm at that angular position.

Segmentation error is the largest source of error in the tendon moment arm measurements. We manually obtain the center of the tendon and manually segment the bones. Most error is due to the difficulty in determining structures in the image. Despite our efforts to optimize image quality, image contrast of the bones and tendons are not always as good as we would like. Also, voxel partial volumes tend to blur edges. Because the effect of segmentation error is difficult to quantify, we are continuing to perform experiments to determine the inter-observer variability.

To date, our moment arm measurements are well within the range of previously reported results obtained by other methods. Also, the repeatability and inter-observer analyses are within a tolerable range, especially if we do not consider those images having the poorest image quality. Hence, we believe that these 3D methods will provide an effective way to measure finger moment arms in vivo.

Plans for next quarter

We are beginning a more detailed study comparing the 3 methods for measuring moment arm. Because of its simplicity, we will continue to use the 3rd MCP joint. We will image more subjects and analyze them by the 3 methods. We will compare moment arm values, repeatability, image acquisition time, analysis time, etc. We will also compare inter-observer variability of the analysis methods. At the end of this study, we should know better what methods to apply to patients.

1.a.ii. PASSIVE AND ACTIVE MOMENTS

Abstract

During the past quarter, the subject pool in the passive moment measurement study was expanded to 8 able bodied individuals and 6 users of a hand grasp neuroprosthesis (NP). The measurements were made at the metacarpophalangeal (MP) joint of the index finger while the wrist was fixed in seven positions that ranged from 60° of extension to 60° of flexion in 20° increments. Features of the raw moment versus angle plots were computed and compared across wrist positions and across subject populations. The joint stiffness was computed differently than previously reported. Comparing the average results from both populations revealed that at all wrist positions the NP users could not extend their MP joints as far as the able bodied population. Consequently, the average passive range of motion (PROM) for the NP users was less than the average PROM of the able bodied subjects. No significant difference was revealed between the joint stiffness of the NP users and the able bodied population. The passive moment data from each subject were simulated by a computer model that was designed to compute the passive moment as the sum of two components. One of these components has no wrist position dependency while the other component has a linear dependency wrist position. The model allows computation of the percentage of the total passive moment that is due to the extrinsic tendons (wrist position dependent) and due to the MP joint capsule tissues (independent of wrist position). The results show that the tendons play a greater role in restricting MP extension when the wrist is extended than when it is flexed. Also, the percentage of the total passive moment due to tendons at the MP flexion limit is greatest when the wrist is flexed and least when the wrist is extended.

Purpose

The purpose of this project is to characterize the passive properties of normal and paralyzed hands. This information will be used to determine methods of improving hand grasp and hand posture in FES systems.

Report of Progress

Changes in Data Collection and Analysis

The experimental protocol consists of measuring the passive moment at the MP joint of the index finger while the wrist is fixed in seven positions between 60° of extension and 60° of flexion. Previously, some of the subjects were tested at only three wrist positions. These subjects have now been retested at all seven wrist positions. The seven positions make it easier to see how features of the passive moment change with wrist position.

The passive moment versus joint angle plots are fit with the equation,

$$M = a(e^{b(\emptyset - d)} - e^{c(\emptyset - d)}) + f \cdot \emptyset + g. \qquad (1.a.ii.1)$$

In addition to the double exponential, this equation contains a term linear with MP joint angle, $f{\cdot}\emptyset + g$. In general, this equation fits the raw data better than the double exponential alone, as was previously used. Equation 1.a.ii.1 yields six parameters for each moment angle curve. Because these parameters are interdependent, they cannot be directly compared to like parameters from different moment angle curves. Therefore, Equation 1.a.ii.1 is used to compute features of the moment angle curve that can be compared across curves generated at different wrist positions and by different subjects. Six features are computed from Equation 1.a.ii.1 and are shown in Figure 1.a.ii.1.

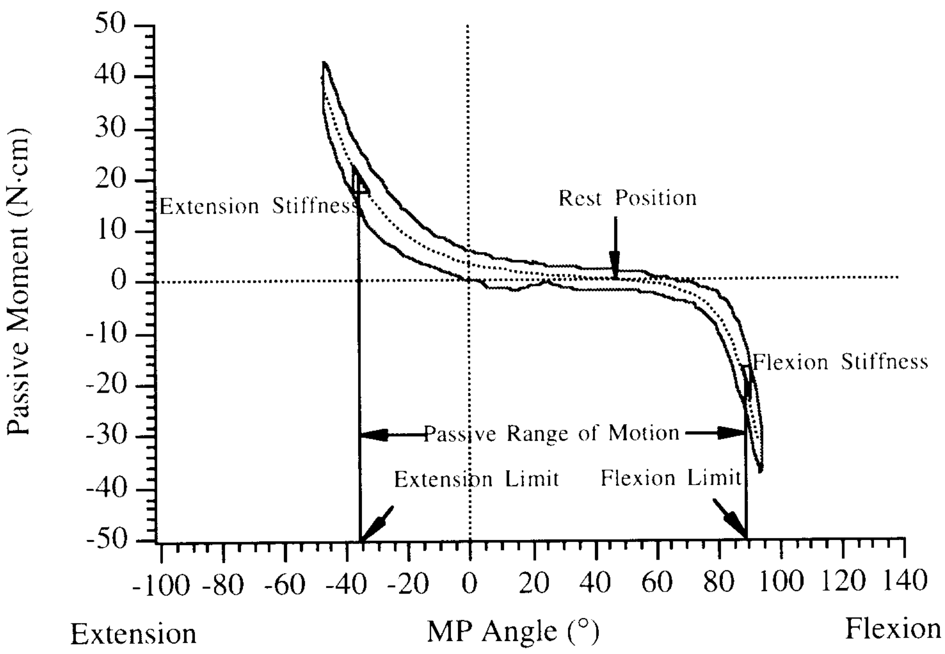

Figure 1.a.ii.1. Six parameters computed for each moment angle curve. These parameters are used to compare moment angle curves measured at different wrist positions and from different subjects.

The rest position (RP) and passive range of motion were defined in a previous report. The extension limit and flexion limit are defined as the MP angles at which the passive moment reaches 20 N·cm and - 20 N·cm, respectively. They are the angles which define the PROM. Likewise, the extension stiffness and flexion stiffness are defined as the slope of the moment angle curve at 20 N·cm and - 20 N·cm, respectively. These stiffnesses are computed by taking the derivative of Equation 1.a.ii.1 and evaluating the derivative at the angles that define the extension and flexion limits. Previously, stiffnesses were computed as the slopes of line segments connecting various levels of passive moment along the curve fit.

In order to separate the total passive moment into components that are produced by extrinsic tendons and components that are produced by tissues of the joint capsule, a computer model was developed to simulate each subject's experimental data. The model computed the total passive moment as the sum of two equations. One of these equations had terms with linear relationships to wrist position, while the other equation was independent of wrist position. The moment computed by the wrist dependent equation is thought to correspond to that part of the total passive moment that is due to the deformation of tissues that cross the wrist as well as the MP joint. Such tissues would include the extrinsic tendons such as the extensor digitorum communis, extensor indicis, flexor digitorum profundus, and flexor digitorum superficialis. The moment computed by the equation with no wrist position dependent terms is thought to correspond to that part of the total passive moment that is due to tissues that do not cross the wrist but do cross the MP joint. Such tissues would be those that constitute the joint capsule as well as the ligaments.

Once the passive moment due to the tendons and the passive moment due to the joint capsule were determined separately, the relative contributions that each made to the total passive moment were computed.

Results

A. Comparing NP User and Able Bodied Subject Averages

The averages of each of the six parameters shown in Figure 1.a.ii.1 were computed for the NP users and for the able bodied subjects. The average extension limit was significantly less ($p<0.05$) for the NP users than for the able bodied individuals as shown in Figure 1.a.ii.2. However, the average flexion limit for both populations was not significantly different. Therefore, the average passive range of motion, like the extension limit, was also less for the NP user population than for the able bodied subjects. Only at flexed wrist positions was the NP user's average rest position more flexed than that of the able bodied subjects. The average extension and flexion stiffnesses were not significantly different between the two populations.

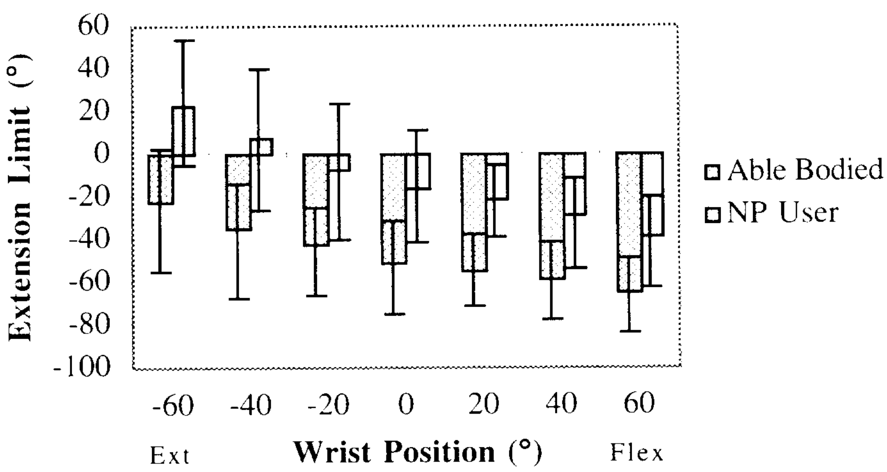

Figure 1.a.ii.2. Average and range of the extension limit for both the able bodied and NP user populations. The average extension limit of the NP users is less than the average extension limit of the able bodied subjects.

B. Identifying Trends Due to Wrist Position

On average, the greatest MP extension was possible when the wrist was maximally flexed and the least MP extension occurred when the wrist was maximally extended. Conversely, the greatest MP flexion was possible when the wrist was extended and the least MP flexion occurred when the wrist was flexed. The rest position had a nearly linear relationship to wrist position, becoming more extended as the wrist flexed. These trends are shown in Figure 1.a.ii.3.

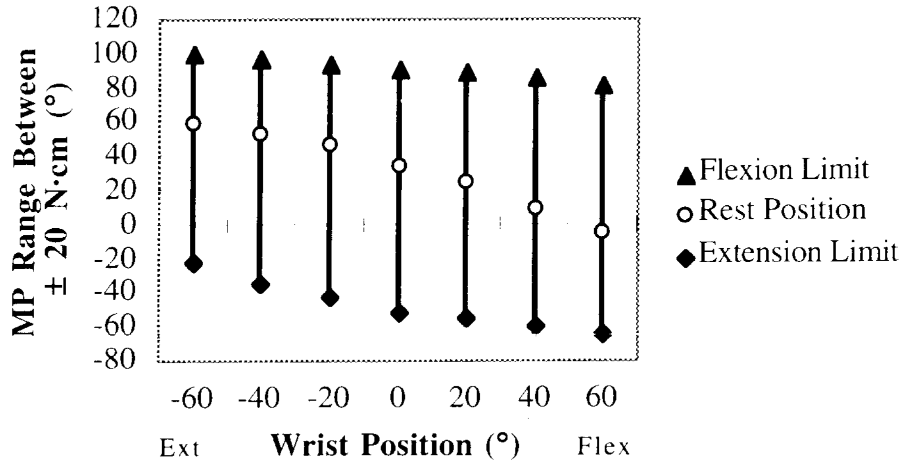

Figure 1.a.ii.3. Average MP range between ± 20 N·cm for the able bodied population. The entire range of motion shifts toward extension as the wrist is flexed.

There was also a trend in the way the flexion and extension stiffnesses changed with wrist position and how they changed relative to one another with wrist position. On average, when the wrist was extended, the flexion stiffness was greater than the extension stiffness. However, as the wrist flexed, the extension stiffness increased and the flexion stiffness decreased so that they were about equal at 60° of flexion. This trend is shown in Figure 1.a.ii.4. Such a trend suggests that MP joint flexion is limited by stiffer tissues when the wrist is extended than when the wrist is flexed and that MP joint extension is limited by stiffer tissues when the wrist is flexed than when the wrist is extended. It also suggests that MP joint flexion is limited by stiffer tissues than MP joint extension when the wrist is extended, and that tissues of about the same stiffness limit both MP joint flexion and extension when the wrist is flexed. The stiffer tissues are probably the tissues of the joint capsule and ligaments, while the more compliant tissues are likely to be muscle/tendon units.

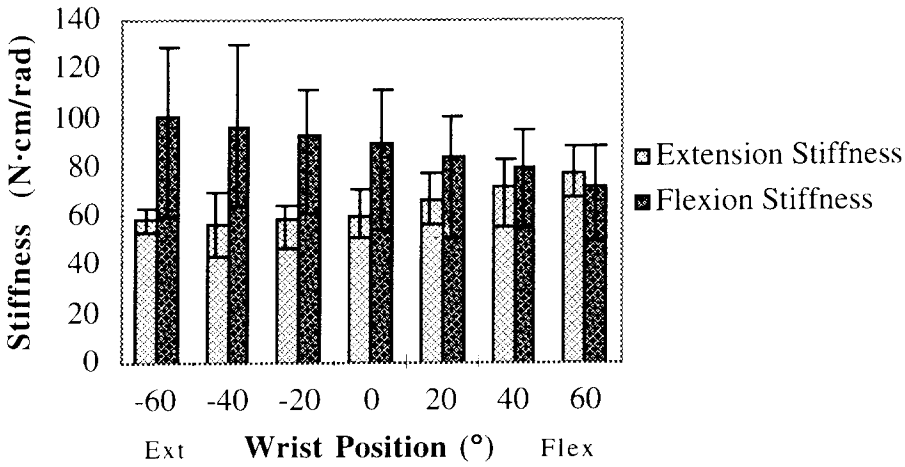

Figure 1.a.ii.4. Average and range of flexion and extension stiffnesses for the able bodied population. Stiffer tissues limit MP flexion when the wrist is extended, but the MP flexion limit becomes more compliant as the wrist is flexed.

C. Results of the Computer Simulations of Experimental Data

Each subject's experimental data were simulated by the computer model. Therefore, the passive moment due to extrinsic tendons and the passive moment due to the tissues of the joint capsule and ligaments were computed for each subject at each wrist position. An example of the computer results for a single subject at three wrist positions is shown in Figure 1.a.ii.5. Each subplot of this figure corresponds to a different wrist position. In each subplot four traces are plotted. The four traces are: 1) the data points (dots) extracted from the curve fits to the raw moment angle curves; this data is the input to the model and is to be simulated by the model, 2) the passive moment computed by the model that does not change with wrist position (dotted line); this is the trace corresponding to the passive moment generated by the joint capsule, 3) the passive moment computed by the model that shifts with wrist position (dashed line); this trace corresponds to the passive moment created by the extrinsic tendons, and 4) the sum of the previous two traces (solid line); this trace is the simulated total passive moment. How well the simulated total passive moment matches the experimental data points depends on how well the computer algorithm solved the equations.

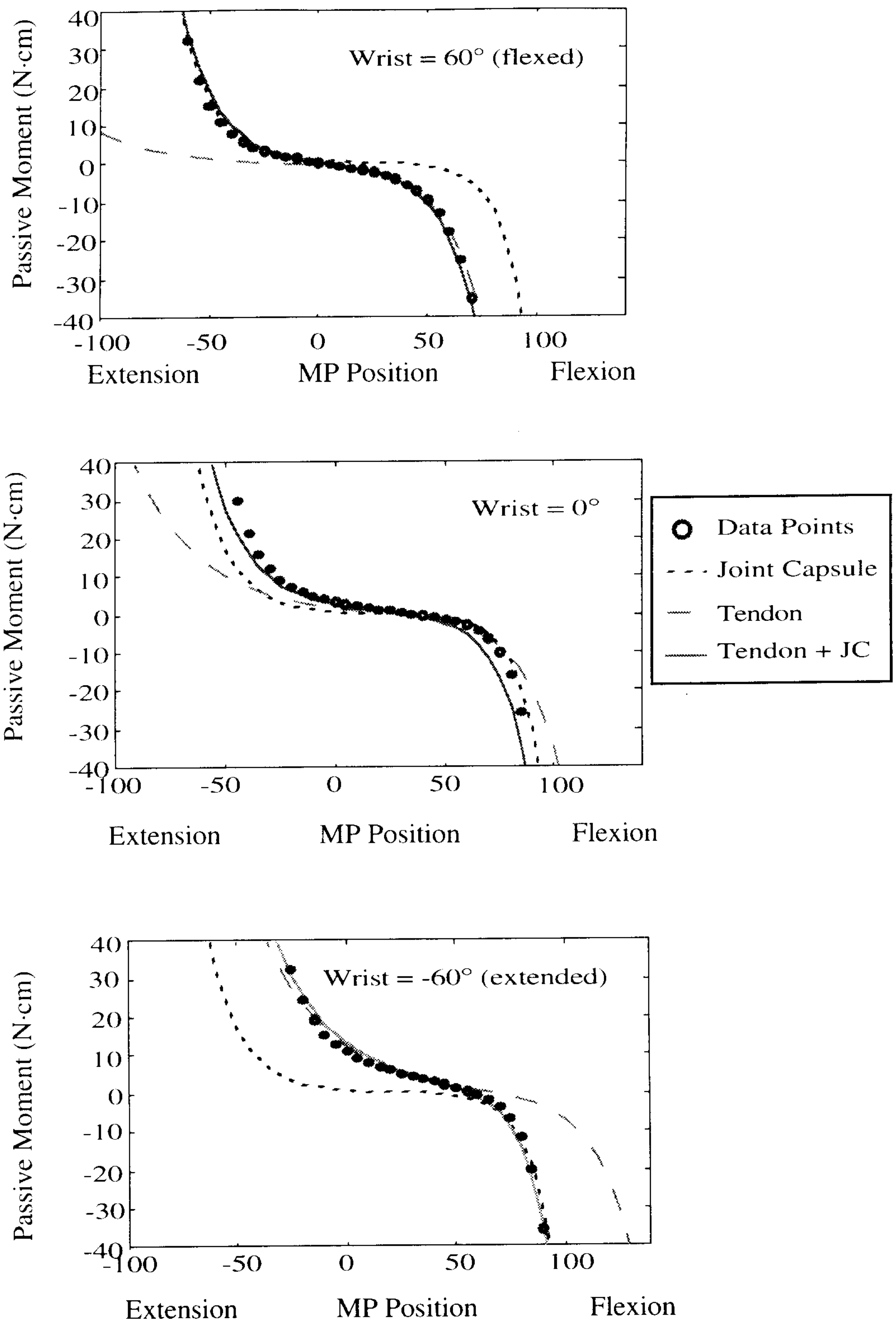

Figure 1.a.ii.5. Example of one subject's computer simulation results plotted at three wrist positions.

This example shows that with a flexed wrist, the MP extension limit is defined by the joint capsular passive moment and the MP flexion limit is due almost entirely to tendons. Conversely, when the wrist is extended, the MP extension limit is due to tendon while MP flexion is limited by the joint capsule. At wrist positions in between these two extremes, the MP flexion and extension limits are due to combinations of tendon and joint capsular tissues.

For two subjects, the percentage of the total passive moment that is due to tendon when the MP joint reaches its flexion and extension extremes were computed at the seven wrist positions. Subject JK is a 26 year old able bodied male and subject JL is a 24 year old male with C5 level spinal cord injury. JL's proximal interphalangeal joints are tightly contracted. Figure 1.a.ii.6 shows that tendon contributes more to the total passive moment at MP extension when the wrist is extended than when the wrist is flexed. However, at the MP flexion extreme, the tendon comes more into play when the wrist is flexed than when it is extended. At each wrist position, JL's tendons restrict MP motion more than JK's tendons.

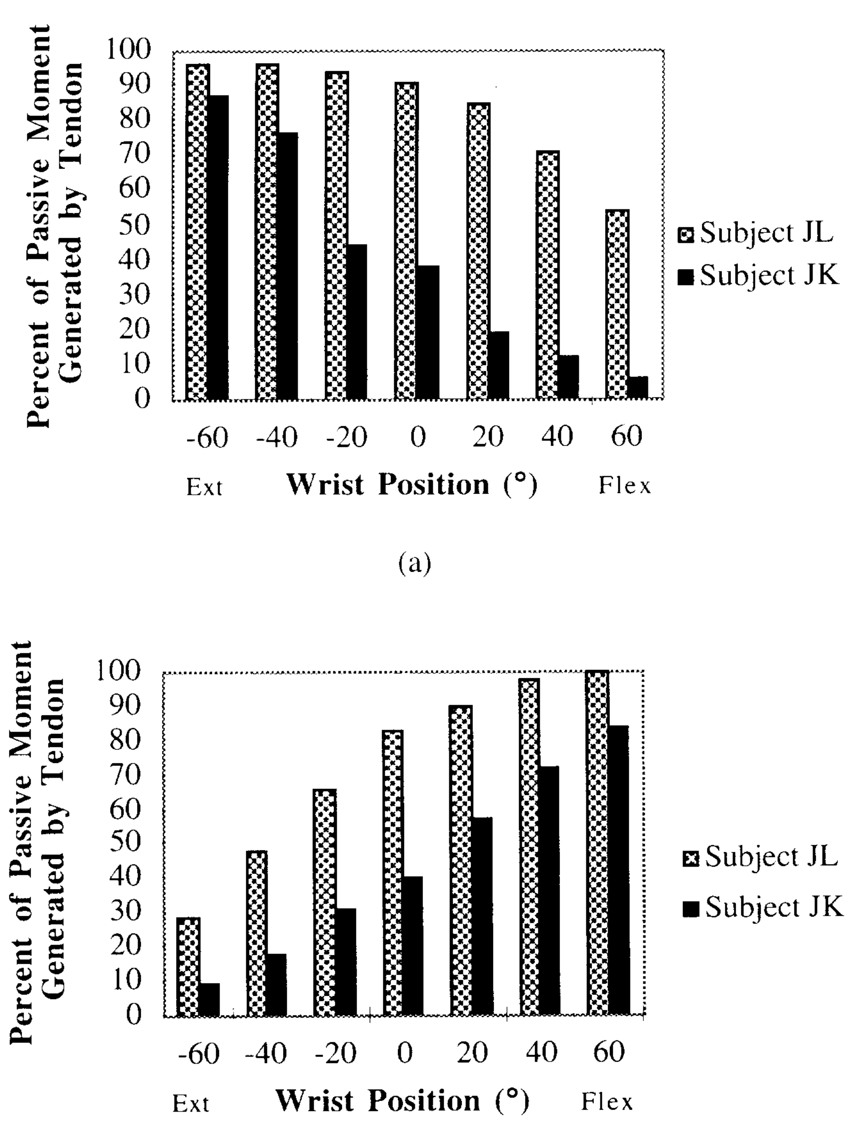

Figure 1.a.ii.6. For two subjects, the percent of the total passive moment that is due to tendon at: (a) MP extension extreme and (b) MP flexion extreme.

The results of this model could help clinicians know whether the source of abnormal passive properties is extrinsic tendon or tissues of the joint capsule. For example, Figure 1.a.ii.6a shows that JL's data is approximately equal to JK's data at a wrist position shift of 80°. That is JK's data at a wrist position of -60° is about equal to JL's data at a wrist position of 20°. An 80° change in wrist position results in a change in flexor length of about 2 centimeters (assuming a flexor moment arm at the wrist of about 1.5 cm). Therefore, one may conclude that JL's flexor tendons are about 2 cm shorter than JK's flexor tendons.

Plans for Next Quarter

Additional experiments done with able bodied subjects will help more clearly define the normative parameter values. Longitudinal studies will be begun to show how the NP users' passive properties change over time. Pre and post surgery measurements will be made to show the effect of surgery on the passive moment characteristics. The equations in the computer model will be expanded to include dependencies upon the interphalangeal joints as well as the wrist. Studies at other joints in the hand will be begun.

1. b. BIOMECHANICAL MODELING: ANALYSIS AND IMPROVEMENT OF GRASP OUTPUT

Abstract

This project is just beginning. Two important tools are being developed in order to make the necessary biomechanical measurements with individual patients. First, the use of magnetic resonance images to determine joint moment arms is described in Section 1.a.i. Secondly, the measurement of passive moments across all joints of the hand is described in Section 1.a.ii.. When these tools are complete, we will begin making measurements on both normal and paralyzed patients.

Objective

The purpose of this project is to use the biomechanical model and the parameters measured for individual neuroprosthesis users to analyze and refine their neuroprosthetic grasp patterns.

Report of Progress

The results from both the magnetic resonance imaging project and the passive moment project will be combined in the biomechanical model to accomplish the goal of improving grasp output. During this quarter, we hired Wendy Murray, Ph.D., to coordinate this project. Her initial goal will be to incorporate the passive moment data into the biomechanical model of the hand.

2. CONTROL OF UPPER EXTREMITY FUNCTION

Our goal in the five projects in this section is to either assess the utility of or test the feasibility of enhancements to the control strategies and algorithms used presently in the CWRU hand neuroprosthesis. Specifically, we will: (1) determine whether a portable system providing sensory feedback and closed-loop control, albeit with awkward sensors, is viable and beneficial outside of the laboratory, (2) determine whether sensory feedback of grasp force or finger span benefits performance in the presence of natural visual cues, (of particular interest will be the ability of subjects to control their grasp output in the presence of trial-to-trial variations normally associated with grasping objects, and in the presence of longer-term variations such as fatigue), (3) demonstrate the viability and utility of improved command-control algorithms designed to take advantage of forthcoming availability of afferent, cortical or electromyographic signals, (4) demonstrate the feasibility of bimanual neuroprostheses, and (5) integrate the control of wrist position with hand grasp.

2. a. HOME EVALUATION OF CLOSED-LOOP CONTROL AND SENSORY FEEDBACK

Abstract
The purpose of this project is to deploy an existing portable hand grasp neuroprosthesis capable of providing closed-loop control and sensory feedback outside of the laboratory. In this quarter, the portable system configured for grasp force sensory feedback was deployed for a day-long trial in a neuroprosthesis user. No quantitative evaluations were performed, but the user's subjective feedback was positive. The current population of neuroprosthesis users was reviewed to identify candidates for longer evaluations.

Purpose
The purpose of this project is to deploy an existing portable hand grasp neuroprosthesis capable of providing closed-loop control and sensory feedback outside of the laboratory. The device is an augmented version of the CWRU hand neuroprosthesis, and was developed and fabricated in the previous contract period. The device utilizes joint angle and force sensors mounted on a glove to provide sensory information, and requires daily support from a field engineer to don and tune. The portable feedback system is not intended as a long term clinical device. Our goal, rather, is to evaluate whether the additional functions provided by this system benefit hand grasp outside of the laboratory, albeit with poor cosmesis and high demands for field support.

Report of Progress
Following the day-long trial of the portable closed-loop system (PCLS) in a passive mode last quarter and the repair of the PCLS power supplies, the PCLS was deployed for day-long trials of grasp-force sensory feedback by an able-bodied user and a neuroprosthesis (NP) user. The trial with the able-bodied subject was conducted only to confirm proper operation of the device prior tests with the NP user. The NP user was tested while he was admitted to MetroHealth Medical Center for rehabilitation and training following implantation of the NP. NeuroControl Corporation, the sponsors of the NP clinical trials, agreed to allow this NP user to don the PCLS provided that it could be removed if it interfered at any time with the users training.

The NP user, *J*, had persistent difficulties with skin hypersensitivity and irritation from tape used to secure the electrode. On the first day, suitable and comfortable stimulation was achieved by hydrating the skin adequately on a site higher on the neck than used previously (just below the hairline) and using Tegaderm rather than tape to hold the electrode. Stimulation did cause pricking or stinging occasionally when *J* leaned to the side during weight shifts. On the second day, a site on top of trapezius was chosen that seemed less prone to movement, and stimulation was never painful. Overall, *J* responded positively, though not enthusiastically, to the force feedback, and would have liked a longer trial period.

The problems with stimulus comfort and electrode mounting suggested using self-adhesive, Ag/AgCl gel electrodes rather than stainless steel. To assess this possibility, infant EKG electrodes were used for stimulation on 3 able-bodied subjects. Although the phase duration had to be increased from 30 μs to 60-120 μs, the stimulation was not perceptibly different. Self-adhesive electrodes will likely be used in subsequent trials.

Last, we reviewed the status and characteristics of all current NP users in the Cleveland program to identify potential candidates for the complete protocol. Users were reviewed regarding their injury level (the closed loop control system requires a C5 user wearing a wrist brace), tactile sensation on the thumb and index finger of the NP hand (two-point threshold, sensation should be absent for users of sensory feedback), sensation on the contralateral thorax (Semmes-Weinstein filament threshold, sensation should be normal for application of the feedback stimulation), residence (within driving distance preferred), and ease of working with the user in previous laboratory visits. The latter rating was subjective and rendered by the program's hand therapist, but was important since the PCLS evaluation protocol is lengthy and requires a very substantial interaction with the NP user. Only 2 of the users wear a wrist brace (#10, #13; see table below), and both live out of state. Therefore, the users were rated for participation in sensory feedback evaluation independent of injury level. Each of the remaining factors was scored on a 3-level Likert scale (-1, 0, +1), and the scores were simply added to yield a rough, relative indicator of the users' potential. The results are summarized in the table below. The most promising user (#2) is scheduled for an interview in two weeks to solicit participation. User #12 is well-suited to the study, but is currently participating in several studies of proximal stimulation and control. However, the study has been described to that user, and he will be asked to participate.

			Digit 2PT		Trunk SW			
User	*Rating*	*Level*	*d1*	*d2*	*C3*	*C4*	*Address*	*B*
1	0	C6-	12	13	2.83	4.31	Madison OH	-1
2	4	C5	NPT	NPT	2.83	2.83	Maple Hgts OH	1
3	1	C6					Olmstead Falls OH	1
4	0	C6+	3	4	2.83	2.83	Andover OH	
5	2	C6-	1PT	NPT	4.31	3.61	Brunswick OH	0
6	-1	C6	6	10	2.83	2.83		-1
7	-1	C6					Norman OK	1
8	2	C6-	4	7	2.83	2.83	Sheffield Lk OH	1
9	0	C5	1PT	1PT	4.31	4.31	Mercer PA	-1
10	1	C4/C5	NPT	1PT	4.31	4.31	Wheaton MO	0
11	1	C6	5	1PT	2.83	2.83	Erie PA	1
12	3	C6	1PT	NPT	4.31	3.61	Broadview Hgts OH	1
13	2	C5	NPT	NPT	2.83	2.83	Franklin WI	1

2PT = Two point threshold (in mm). 1PT = perceived only 1 point. NPT = no sensation.
SW = Semmes-Weinstein monofilament threshold in standard units. Normal = 2.83.

Plans for Next Quarter
We will complete as much of the evaluation protocol as possible on user #2, if the user consents to participation. Other users will be tested on segments of the protocol as they are available.

2. b. INNOVATIVE METHODS OF CONTROL AND SENSORY FEEDBACK

2. b. i. ASSESSMENT OF SENSORY FEEDBACK IN THE PRESENCE OF VISION

Abstract
The purpose of this project is to develop a method for including realistic visual information while presenting other feedback information simultaneously, and to assess the impact of feedback on grasp performance in the presence of such visual information. In this quarter, all components of the video recording and simulation playback systems are largely complete. The evaluation software needs to be written and the video libraries need to be recorded.

Purpose
The purpose of this project is to develop a method for including realistic visual information while presenting other feedback information simultaneously, and to assess the impact of feedback on grasp performance. Vision may supply enough sensory information to obviate the need for supplemental proprioceptive information via electrocutaneous stimulation. Therefore, it is essential to quantify the relative contributions of both sources of information.

Report of Progress

The video simulation system has 3 major components: (1) a recording system used to create the video clips and accompanying command, force and span data files; (2) a playback system that permits those files to be displayed according to the command signal generated by a test subject; and (3) an evaluation system that implements an acquire and hold task, as in the PCLS study. In this quarter, the first two components were largely completed. The recording system was programmed as a virtual instrument (VI) in LabVIEW. The VI generates a sigmoidal command ramp (voltage vs. time) of adjustable duration, and simultaneously records the forces and spans produced when the command is input to a user's neuroprosthesis. The sigmoidal shape of the ramp narrows the frequency spectrum of the input, and, for sufficiently long ramps, avoids producing output components affected by the dynamics of the neuromuscular system. The recording system also produces audio beeps used to synchronize the analog data to the video frames. The synchronization and averaging of the analog data within each video frame is performed off-line. Prototype software for that processing has been tested, and final software will be completed in the next quarter. The playback system is complete apart from finger span feedback. That is, an able-bodied user can don a shoulder control, generate a command signal and thus "select" the video frame corresponding to that command. At the same time, the command recalls the force produced, which is converted to a voltage and used to modulate the amplitude of the electrocutaneous feedback signal according to the conversion described in previous reports. If the command is not modified, however, the simulated NP responds instantaneously to the command. Therefore, the command generated by the able-bodied subject is passed through a second-order low-pass filter and a fixed delay to produce a dynamic response commensurate with a real NP.

Plans for Next Quarter

The primary remaining task is to program the software for evaluating the effect of grasp force (and/or finger span) feedback on performance of a grasp-and-hold task. Development of that software will begin in the next quarter. We will also collect a trial library of video clips, and finalize the recording and playback components of the video simulation system.

2. b. ii. INNOVATIVE METHODS OF COMMAND CONTROL

Abstract

During this quarter we conducted experiments with three subjects to test the performance of a 2-element strain gage mounted on the thumbnail as contact sensor. One gage was oriented perpendicular to the thumb and the other parallel to the thumb. The output of a strain gage was recorded while the subjects performed the task of object grasp, transport, and release. The results indicated that the output of both gages was correlated with contact and grasp force, but appeared relatively insensitive to elevation.

Purpose

The purpose of this project is to improve the function of the upper extremity hand grasp neuroprosthesis by improving user command control. We are specifically interested in designing algorithms that can take advantage of promising developments in (and forthcoming availability of) alternative command signal sources such as EMG, and afferent and cortical recordings. The specific objectives are to identify and evaluate alternative sources of logical command control signals, to develop new hand grasp command control algorithms, to evaluate the performance of new command control sources and algorithms with a computer-based video simulator, and to evaluate neuroprosthesis user performance with the most promising hand grasp controllers and command control sources.

Report of Progress

The following conference paper was submitted during this quarter

Grill, W.M., C.L. Van Doren (1997) Detection of object contact during grasp using nail-mounted strain sensors. Proc. 19th Ann. Int. Conf. IEEE-EMBS.

During this quarter we conducted experiments to evaluate the performance of thumbnail-mounted strain gage pairs as contact and grasp force detectors.

METHODS

All subjects read and signed an informed consent, and all procedures were reviewed by the Institutional Review Board of MetroHealth Medical Center.

A metal foil strain gage rosette, with 2 perpendicular gages, (SG-3/350-XY11, Omega Engineering, Stamford, CT) was glued to the thumbnail using cyanoacrylate cement. The array was oriented with 1 gage approximately perpendicular to the long axis of the thumb and 1 gage approximately parallel to the long axis of the thumb. A custom-built 2-channel instrumentation amplifier, based around the Analog Devices 1B31AN chip, was used to provide excitation voltage, amplification, and low-pass filtering of the strain gage signals. The two channels of the amplifier had well matched input-output properties (fig. 2.b.ii.1). Subjects were also instrumented with a large carbon rubber surface electrode (6282, 3M Health Care, St. Paul, MN) that formed 1 pole of a continuity detector. The other pole of the continuity detector was formed by conductive foil placed on one side of the test object. A custom-built detector generated a signal when the hand-object circuit was completed and was used to provide an independent measure of when the thumb contacted the object to be grasped. In addition to the standard cylinders and blocks (see QPR#2) some trials with the instrumented "book", which provides a voltage output proportional to the grasp force, were also included. [Memberg and Crago, 1997]. The test object was placed on a table switch that generated a TTL signal when the object was lifted off the table.

Each trial consisted of the subject reaching out, grasping, lifting the object, transporting it to another location 30 cm above the first, and releasing the object. The object was then re-grasped, lifted, and returned to the starting point. The beginning of a trial was signaled by an audible "GO" signal from the experimenter.

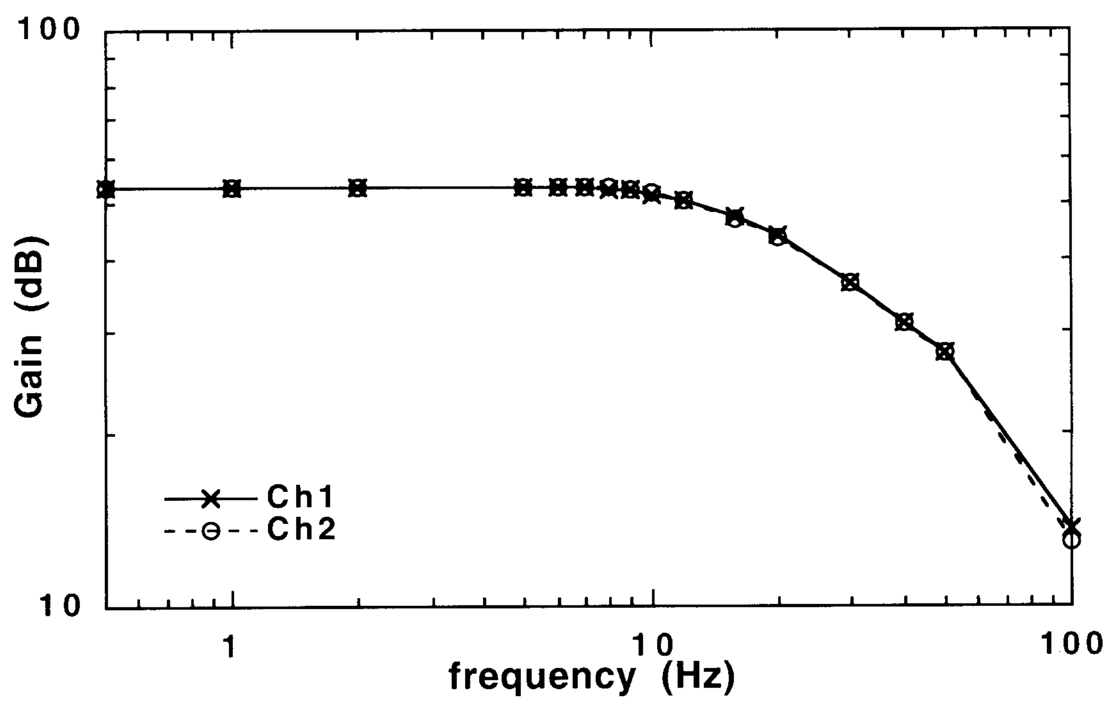

Figure 2.b.ii.1: Bode plot of the input-output characteristics of the 2 channels of the strain gage amplifier.

RESULTS

The output of the two strain gages (longitudinal and transverse), the grasp force, the contact signal, and the lift-off signal are shown in figures 2.b.ii.2 and 2.b.ii.3 for two different subjects. In both cases the subjects were grasping the instrumented book [Memberg and Crago, 1997] between the thumb and the side of the first finger using lateral grasp. In the first case (2.b.ii.2A) the gage was well mounted and both gages exhibit robust responses, while in the second case (2.b.ii.3A) the gage was not well mounted (i.e., when the gage was removed there was an area that was not bonded to the nail), and while the transverse gage generated a strong response, the longitudinal gage exhibited a lower gain.

In both subjects the strain signal appeared to be well correlated with the grasp force, and the leading edge of the strain signals was coincident with the contact signal. In contrast to the results reported in QPR#3, the gages exhibited a low sensitivity to elevation of the hand. The output of the gages, as well as the difference between the transverse and longitudinal signals (shown at a greatly increased gain), during overhead reach is shown for the two subjects in figs. 2.b.ii.2B and 2.b.ii.3B. In the first case (fig. 2.b.ii.2B), the subject touched the object, lifted their hand overhead, returned, and then touched the object again. The touch produced a weak response in each gage (note that scale and gain are the same in panels A and B), while the change in elevation produced almost no detectable response at this gain. The touch signal present in the differential strain signal was robust and coincident with the actual contact signal, while the elevation signal was smaller and of a much lower frequency. In the second case, the subject started with their hand on the contact plate, lifted it overhead, and returned it to the contact plate. The elevation signal was undetectable in the strain signals (note that scale and gain are the same in panels A and B), but was apparent in the differential signal. The elevation signal was a low frequency wave with a peak occurring at the center of the "lift-off" signal, which corresponded to when the hand was overhead. In all three subjects the magnitude of the strain signal generated by elevation was an order of magnitude smaller than the strain signals generated during object grasp.

In comparing the output of the strain gages to the output of the instrumented book, it appeared that the strain gage might also function as a grasp force sensor. To evaluate this feature the strain signal was plotted *vs.* the grasp force measured with the instrumented book, with time as the path variable. The plots in figures 2.b.ii.2C and 2.b.ii.3C show these data for the example trials for each subject. The strain gage signal exhibited hysteresis and a variable force gain making it unsuitable as a grasp force sensor. The variable force gain appeared to be strongly dependent on the orientation of the thumb as the object was grasped.

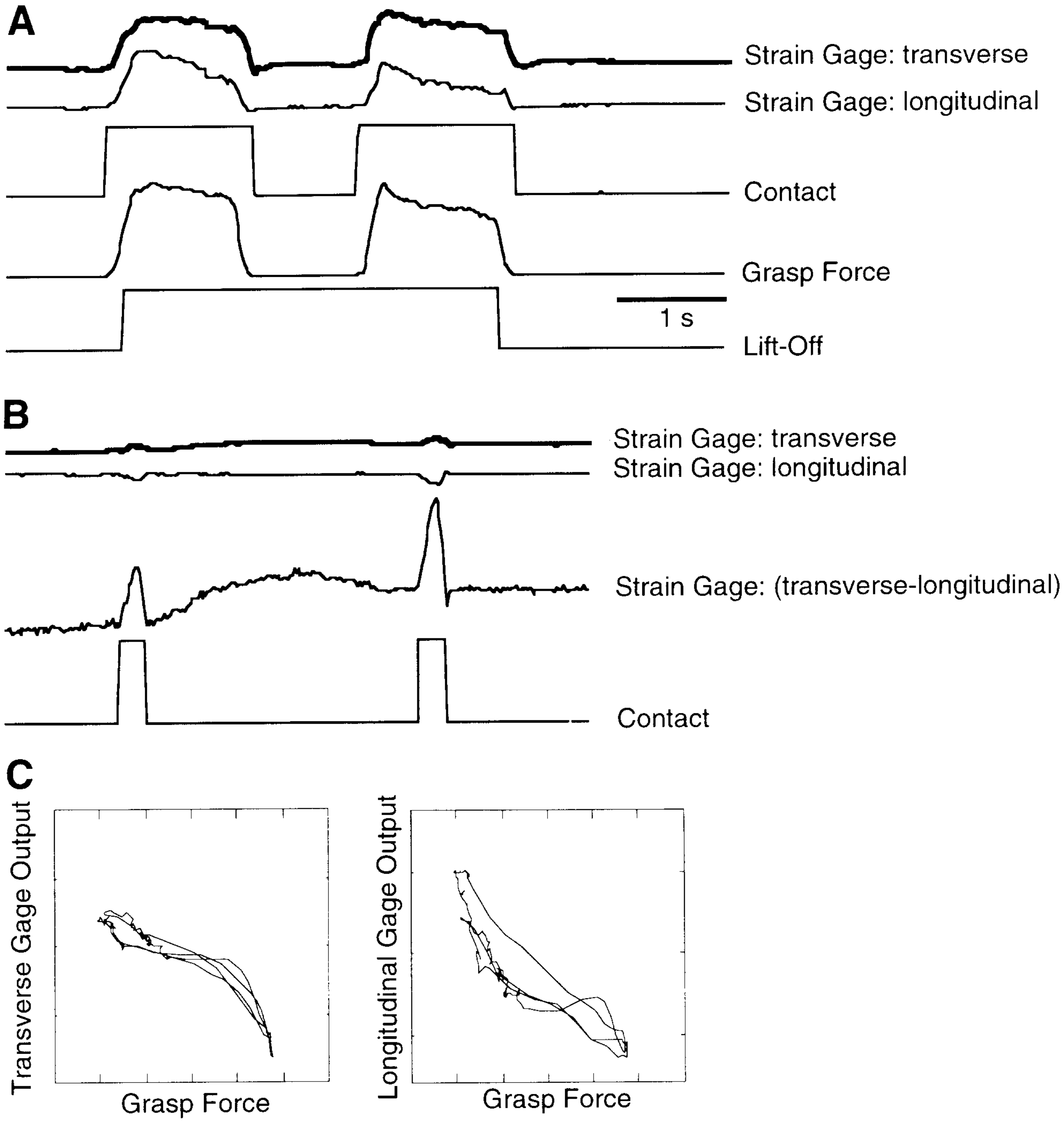

Figure 2.b.ii.2: Output of a thumbnail mounted strain gage pair during the task of grasp, lift, release, grasp, return, release (A) and during overhead reach without an object in the hand (B). (C) Comparison of the strain signal and the output of the grasp force sensor.

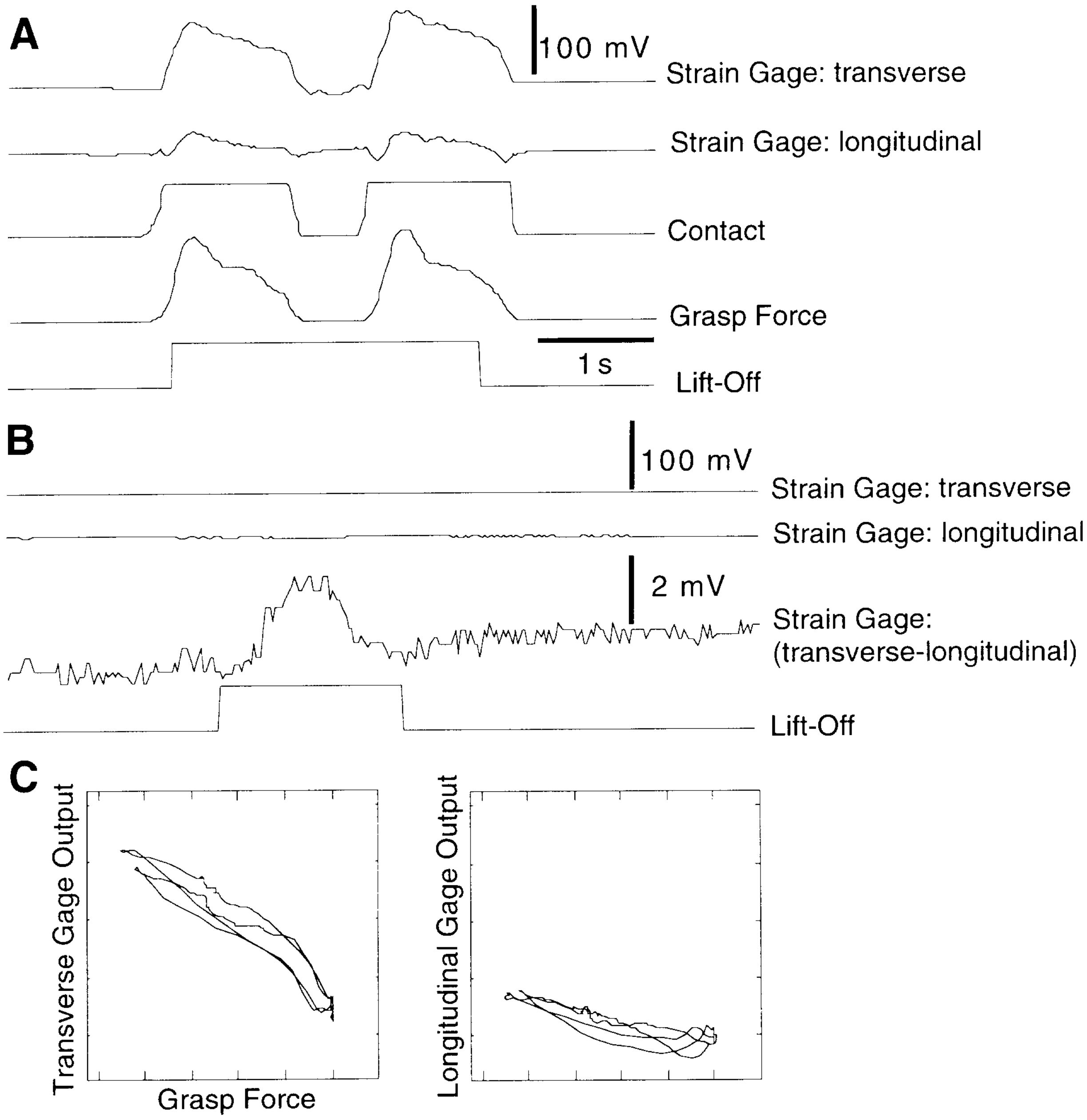

Figure 2.b.ii.3: Output of a thumbnail mounted strain gage pair during the task of grasp, lift, release, grasp, return, release (A) and during overhead reach without an object in the hand (B). (C) Comparison of the strain signal and the output of the grasp force sensor.

Plans for Next Quarter

The results obtained to date indicate that a thumbnail mounted strain gage provides a reliable contact sensor, but has variable sensitivity to hand elevation. During the next quarter we will determine the source of the elevation related strain signal and devise methods to compensate for it.

References

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2. b. iii. INCREASING WORKSPACE AND REPERTOIRE WITH BIMANUAL HAND GRASP

Abstract
Bimanual control of hand grasp was implemented in one person using an implanted stimulator in the contralateral upper extremity. This person had previously been implanted with a implanted stimulator in 1986. The hand function provides palmar grasp with control provided by switches. The individual is currently in the initial period of post-operative muscle conditioning and at home use.

Purpose
The objective of this study is to extend the functional capabilities of the person who has sustained spinal cord injury and has tetraplegia at the C5 and C6 level by providing the ability to grasp and release with both hands. As an important functional complement, we will also provide improved finger extension in one or both hands by implantation and stimulation of the intrinsic finger muscles. Bimanual grasp is expected to provide these individuals with the ability to perform over a greater working volume, to perform more tasks more efficiently than they can with a single neuroprosthesis, and to perform tasks they cannot do at all unimanually.

Report of progress

Implantation of Receiver/Stimulator
:In this quarter a subject (JHJ) received an implantable stimulator in his right arm. This same subject in 1986 received an implantable stimulator in his left arm and has been a participant in our program since 1978. In QPR #2 we related earlier studies that have been done with this subject using percutaneous electrodes. Briefly, this person has C6 function in his left arm and C5 in his right. Percutaneous electrodes which have been implanted in his right arm demonstrated the functional abilities that were possible by use of the neuroprosthesis. These electrodes were removed on March 7, 1997. On March 27, 1997 surgery was performed to implant an 8-channel stimulator which could provide control of the paralyzed muscles. The procedures performed included a revision of a previous transfer of the brachioradialis to the extensor carpi radialis brevis to tighten the tendons. Transfer of extensor carpi ulnaris to the flexor pollicis longus, Zancolli Lasso transfers of the flexor digitorum superficialis of the long ring and small fingers and implantation of the implant stimulator epimysial electrodes were used for the implantation of the abductor pollicis brevis, and flexor digitorum superficialis of the long ring and small muscles (two electrodes) and closed helix intramuscular electrodes were used for stimulation of the extensor digitorum communis, extensor pollicis longus, flexor digitorum profundus, flexor digitorum superficialis of the index, extensor carpi ulnaris and triceps. The procedure was performed without complication and the subject was placed in a splint for several weeks of immobilization. Following this immobilization the splint was removed and gradual exercise was begun to condition the muscles in an exercise pattern. The subject is now in the initial phases of system use, using a two switch system as the command control source. This two switch system was also described in QPR#2.

Functional Evaluation in ADL Tasks:
Activities of Daily Living Tasks were evaluated with this subject in his previous system that had been implemented with percutaneous electrodes. A number of ADL tasks, performed unilaterally, are routinely evaluated and in addition, a number of tasks which both we and the subject thought would benefit from bilateral hand usage were assessed with bilateral control. They include opening a jar, answering a phone and writing messages, cutting food, pouring from a bottle, and placing a letter in an envelope. Two different command control schemes were assessed. One using the switch control previously referred to in QPR#2, and a second using myoelectric signal recorded by surface electrodes from the brachioradialis muscle and using this signal to gait a command ramp up cr down (Peckham, et al. 1980). Since the subject preferred the use of the myoelectric control source, we focused the evaluation on his performance with this command control option.

The subject was trained in each Activities of Daily Living task using the neuroprosthesis with both a unilateral and a bilateral implementation. For scoring, tasks were divided into several phases and each phase was scored for the amount of assistance which was required. Each task was also scored for the amount of assistance which is required, the patient's preference, the quality, ease, and time to perform the task. We found that overall there was no change in the amount of assistance that was needed across the four ADL tasks evaluated, and that the amount of time it took to perform the task decreased for two tasks, and increased for two tasks. Regarding quality, the therapist evaluated that the performance improved in two tasks, was unchanged in two tasks, and became worse in none. This subject's evaluation of both ease and his preference was that he preferred the bilateral implementation in the performance of three tasks, and preferred to use the bilateral implementation in three tasks. For one task it was unchanged in both ease and preference, and for no tasks did he prefer the unilateral implementation.

At this early stage, the evaluation tasks for bilateral control suggest that the scoring methodology that is used to evaluate the activities of daily living is insufficient to distinguish characteristics that both the therapist and the subject finds to be preferable in the bilateral implementation, since both therapist and subject evaluation indicates greater quality and ease of performance as well as preference for the bilateral implementation.

Plans for Next Quarter

During the next quarter, more focus will be placed on the evaluation of the intrinsic muscles in the hand grasp to provide improved finger extension. This will include measurements of joint angle and contact and grip force with and without the intrinsic muscles. In addition, effort will be directed to the evaluation of alternative methods of command-control to allow for an intuitive and easy control of the bimanual system.

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2. b. iv CONTROL OF HAND AND WRIST

Abstract

Independent grasp and wrist control in a hand grasp neuroprosthesis is compromised by moments at the wrist generated by grasp activation, gravity, and the presence of objects in the grasp. Since the interaction between hand grasp and wrist movement is somewhat predictable, a feedforward controller was designed with artificial neural networks to compensate for the grasp/wrist interaction. Computer simulations with a biomechanical model of the hand and arm were performed to evaluate the feedforward controller. The simulations revealed that in the absence of unpredictable disturbances, the feedforward controller was able to generate independent control of lateral hand grasp and wrist movement. An additional input to the wrist module representing arm orientation eliminated the errors in wrist angle due to gravity effects. Grasp and wrist errors due to unpredictable disturbances (e.g. large moments at the wrist generated by an object in grasp, muscle fatigue) could be reduced by the addition of voluntary wrist extension, and closed-loop feedback.

Purpose

The goal of this project is to design control systems to restore independent voluntary control of wrist position and grasp force in C5 and weak C6 tetraplegic individuals. The proposed method of wrist command control is a model of how control might be achieved at other joints in the upper extremity as well. A weak but voluntarily controlled muscle (a wrist extensor in this case) will provide a command signal to control a stimulated paralyzed synergist, thus effectively amplifying the joint torque generated by the voluntarily controlled muscle. We will design control systems to compensate for interactions between wrist and hand control. These are important control issues for restoring proximal function, where there are interactions between stimulated and voluntarily controlled muscles, and multiple joints must be controlled with multijoint muscles.

Report of progress

The following conference paper was submitted:

Adamczyk, M.M. and Crago, P.E. (1997) "Integrated hand/wrist control in a neuroprosthesis for individuals with tetraplegia", Proc. 19th Ann. Int. Conf. IEEE-EMBS.

Functional neuromuscular stimulation can restore hand function to tetraplegics with a spinal cord injury at the C5/C6 levels [1]. In terms of wrist extension, individuals with an injury at the C6 level maintain some voluntary control due to innervation of the extensor carpi radialis longus and extensor carpi radialis brevis (ECRL/ECRB). For an injury at the C5 level, these muscles are dennervated and cannot be stimulated. However, wrist extension can be provided to this population by performing one or more of the following procedures: (1) voluntary tendon transfer of the brachioradialis (BRD) to ECRB [2]; (2) electrical stimulation of the extensor carpi ulnaris (ECU); and (3) stimulated tendon transfer of the ECU to ECRB [3].

Incorporating independent control of wrist movement in the hand grasp neuroprosthesis (via voluntary and/or stimulated wrist extension) will benefit the user in several ways. For one, if a tenodesis grasp can be duplicated in the neuroprosthesis (grasp opening during wrist flexion, and grasp closing during voluntary wrist extension), individuals will have a more natural and stronger hand grasp [2]. In addition, users with inadequate wrist extension must don a wrist-hand orthosis to stabilize the wrist [4]. The orthosis is not cosmetically acceptable to most users, and restricts hand function. Providing independent wrist control would eliminate the need for the orthosis, and allow free wrist movement.

The wrist extension strength needed to allow independent control of hand grasp and wrist movement will vary with grasp strength, forearm orientation in the gravitational field, muscle fatigue, and load in the hand. Since the hand grasp muscles are controlled by the hand grasp neuroprosthesis, the effect their stimulation has on wrist moment balance is somewhat predictable. Thus, a feedforward controller might be able to model the interaction between hand grasp and wrist movement; and thus set the stimulation patterns of the muscles based on the knowledge of the interaction. This way, grasp opening/force will not have a significant effect on wrist position and visa versa. Compensation for unknown disturbances (e.g. gravity, muscle fatigue, object in grasp) may be provided by an arm orientation input to the controller, voluntary effort, or the addition of feedback control.

METHODS

Design of Feedforward Controller

The purpose of the feedforward controller is to select the stimulation levels of the hand and wrist muscles based on an interaction model so that grasp opening/force will have a minimum effect on wrist position. A feedforward controller is desirable since no external sensors will be required, thus improving cosmesis and reducing complexity. The design of the feedforward controller is divided into two stages: a coordination network and an interaction network (Figure 2.b.iv.1). The function of the coordination network is to set the grasp and wrist posture based on subject input. The inputs from the subject are grasp mode (palmar or lateral grasp), grasp command, and wrist position. The relationships from grasp command to grasp force and opening (i.e. grasp template) were implemented analytically based on those designed for neuroprosthesis users. Wrist position was defined as being either constant as grasp command increased, or changing in parallel with hand grasp to mimic tenodesis grasp.

The function of the interaction networks is to select the stimulation levels of the hand extrinsic muscles and a wrist extensor to produce the desired combination of grasp and wrist angle, taking their interactions into account. The interaction networks were divided into three modules to control the wrist, thumb, and index finger independently. The inputs to each module are the primary grasp/wrist parameter that module is controlling, and any secondary grasp/wrist parameters that will have an effect on the primary parameter. For example, the primary input to the wrist module is wrist angle. However, the wrist module also has the stimulation levels of the flexor digitorum superficialis (FDS), flexor pollicus longus (FPL), extensor pollicus longus (EPL), and arm orientation as secondary inputs, since stimulation of the hand extrinsic muscles as well as gravity will affect wrist angle. The output of the modules is the stimulation level of the muscle controlling the primary grasp/wrist parameter. Using the wrist module as an example again, the output is the stimulation of the ECRB needed to reach the desired wrist angle.

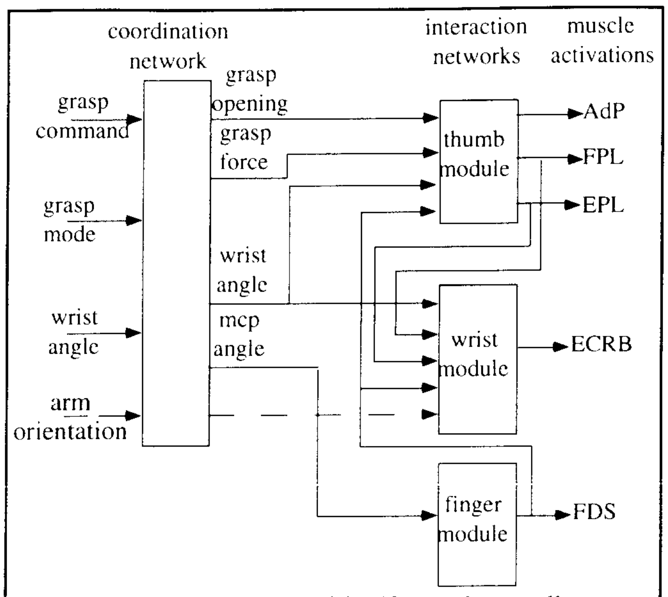

Fig. 2.b.iv.1. Design of feedforward controller.

The interaction networks were implemented with radial basis artificial neural networks (ANN). ANN were chosen since they can model nonlinear systems, the analytical relationship between the input and output does not need to be known, and they can generalize to inputs not part of the training set.

Training of Interaction Networks

Training data for the interaction networks were obtained by computer simulations with a biomechanical model of the hand and arm [5], [6]. For wrist module training data, the wrist angle was calculated for various stimulation levels of the ECRB, FDS, FPL, and EPL with the arm pronated or neutral. For the thumb module, wrist angle, grasp opening and grasp force were calculated for various stimulation levels of the FPL, adductor pollicus (AdP, activated in parallel with FPL), EPL, and ECRB with the arm neutral. For the index finger module, the metacarpophalangeal (MCP) angle was calculated for different levels of FDS stimulation with the arm neutral. Radial basis artificial neural networks were trained for each module with the MATLAB© neural network toolbox.

Evaluation of Feedforward Controller

The feedforward controller was also evaluated with the biomechanical model of the arm. Lateral grasp templates for the coordination network were designed for two cases: (1) wrist angle held constant at 15° extension as grasp opening and grasp force changed linearly from 0% to 100% grasp command, and (2) wrist extension from 0° to 40° extension as grasp opening and grasp force changed linearly from 0% to 100% grasp command. The desired grasp force, grasp opening, and wrist angle from the grasp templates served as inputs to radial basis neural networks (i.e. the interaction networks). The output stimulation levels of the interaction networks (ECRB, FPL, EPL, AdP, FDS) then served as input to the biomechanical model of the arm. The simulated MCP angle, grasp opening, grasp force, and wrist angle were calculated, along with the root mean square (RMS) error between the desired and simulated values.

The simulations were performed under three conditions: (1) arm in the neutral position and no external disturbances present, (2) arm pronated so that gravity was acting in the wrist flexion direction, and (3) arm pronated along with a 13 N-cm external moment applied at the wrist.

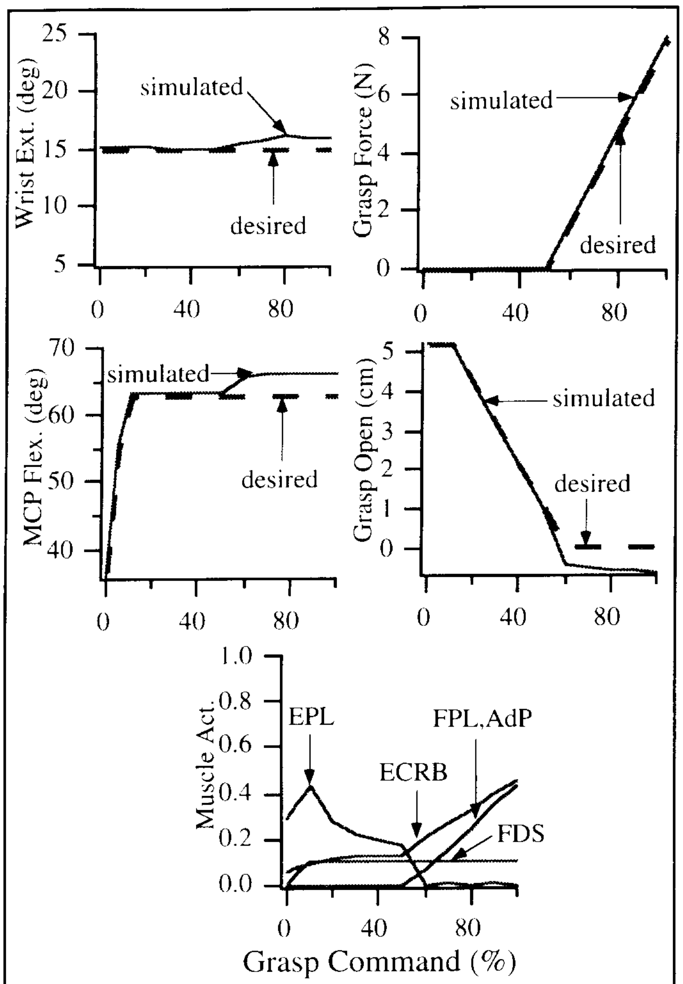

Fig. 2.b.iv.2. Input/output properties for constant wrist angle during grasp without unpredictable disturbances.

RESULTS

Performance without Arm Orientation Input

Figure 2.b.iv.2 displays the desired grasp template and simulated output for case (1) (linear increase in grasp command and grasp force as wrist angle remains at 15° extension) along with the normalized stimulation levels of the muscles as a function of grasp command (i.e. muscle activation map). The RMS errors between the simulated and desired values were small: 0.58° for wrist angle, 0.04 N for grasp force, 0.04 cm for grasp opening (from 0-50%, before contact was made), and 2.1° for MCP angle. The wrist module increased ECRB stimulation in parallel with FPL in order to keep the wrist angle at 15° extension. Similarly, the thumb module modulated the stimulation levels of the EPL, FPL and AdP based on the desired grasp opening and force, taking into account desired wrist angle and FDS stimulation.

Figure 2.b.iv.3 displays the results for case (2) (tenodesis grasp) with the arm both neutral and pronated. The RMS errors between the simulated and desired values when the arm was neutral were again small: 2.2° for wrist angle, 0.04 N for grasp force, 0.06 cm for grasp opening (from 0-50%, before contact was made), and 2.2° for MCP angle. The reason for the slightly higher RMS error in wrist angle for tenodesis is that EPL stimulation extended the wrist beyond the desired angle at 0% and 5% grasp command. In order to reach the desired wrist angle, a wrist flexor would also have to be stimulated. Note that the ECRB must be stimulated at higher levels in order to overcome wrist flexion and mimic tenodesis compared to when a constant wrist angle is required.

When the arm was pronated so that gravity was acting in the wrist flexion direction rather than the ulnar direction, the wrist angle remained flexed beyond 0° until 100% grasp command, and grasp opening decreased. This resulted in significant errors in wrist angle and grasp opening (RMS error for wrist angle = 37°, RMS error for grasp opening = 1.7 cm).

Performance with Arm Orientation Input

Figure 4 displays the performance for case (2) (tenodesis grasp) when the arm was pronated and arm orientation was an input to the wrist module. Adding arm orientation as an input to the wrist module resulted in a wrist angle almost identical to the desired angle (RMS error = 0.5°). The left muscle activation map was generated by the modules with the arm pronated, and the right muscle activation map was generated by the modules with the arm neutral. Note that the wrist module increased the ECRB stimulation in order to compensate for arm orientation (difference in the two muscle activation maps), and that the muscle activation maps generated when the arm was neutral were nearly identical regardless of whether arm orientation was an input to the wrist module. Grasp opening was increased in the pronated orientation due to removing the gravitational thumb flexion moment, but there was almost not effect on grasp force.

Figure 2.b.iv.5 displays the effects of an external moment of 13 N-cm applied at the wrist. In these simulations, a tenodesis grasp was desired (case 2), and the arm was pronated. Arm orientation as an input

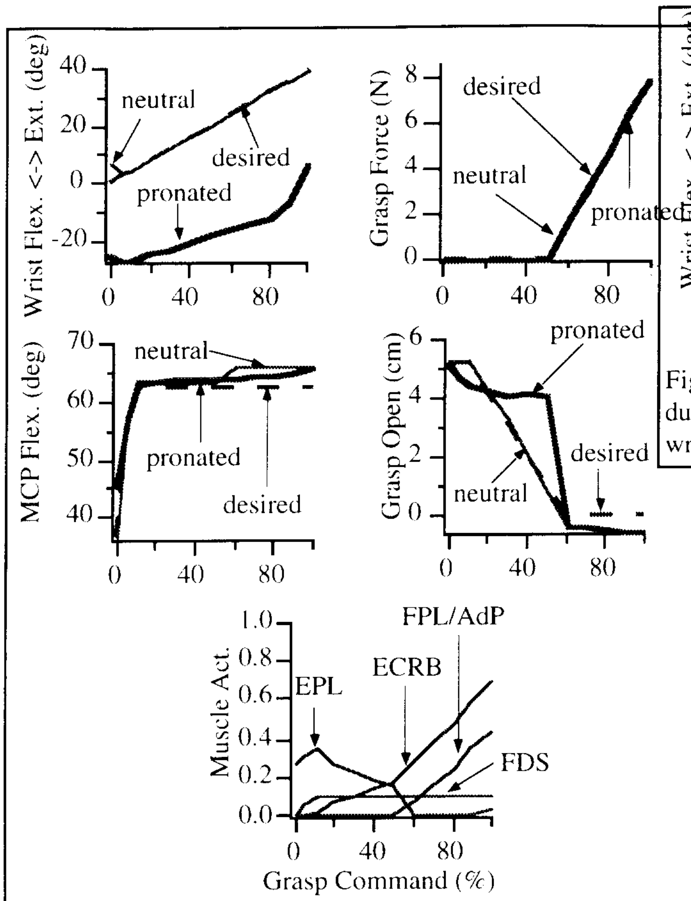

Fig. 2.b.iv.3. Input/output properties for tenodesis grasp with the arm neutral and pronated.

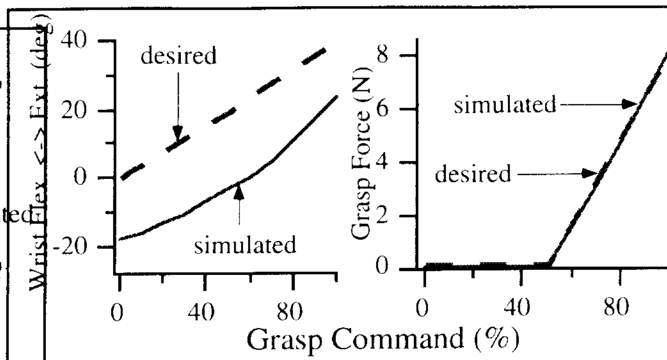

Fig. 2.b.iv.5. Input/output properties for tenodesis grasp during arm pronation and 13 N-cm external moment at the wrist.

to the wrist module compensated for wrist flexion due to gravity. The external moment applied at the wrist, though, caused additional wrist flexion. However, the error in wrist angle (RMS error = 21°) was not as large as that generated by gravity when arm orientation was not an input to the wrist module. Again, the error between the desired and simulated grasp force was small (RMS error = 0.1N).

DISCUSSION

The feedforward controller was successful in both maintaining a constant wrist angle during changes in grasp, and in mimicking tenodesis grasp in the absence of external disturbances. Furthermore, adding an input to the wrist module that represents arm orientation removed errors in wrist angle due to gravity effects. Similarly, errors in grasp opening could be removed by adding arm orientation as an input to the thumb module. Thus, the only disturbances not compensated by the feedforward controller that can have a significant effect on grasp and wrist angle are external moments generated by grasping an object, and muscle fatigue.

The changes in wrist angle and grasp force due to these disturbances, though, might be small enough to allow for the successful completion of a task. For example, wrist extension beyond 0° was still possible when an external moment of 13 N-cm was applied at the wrist (approximate moment a compact disk case applies at the wrist). Thus the simulated tenodesis grasp might allow for the successful grasping of the case, even with the error in wrist angle. This would also apply to other objects that generate a relatively small moment at the wrist (e.g. estimated pen moment at the wrist = 0.7 N-cm, spoon moment at wrist = 1.4 N-cm, computer disk moment at wrist = 2.6 N-cm).

Muscle fatigue will also change the posture with a feedforward control system, depending on the patterns and severity. However, some degree of fatigue will be tolerable, in that tasks could still be completed successfully.

Sensitivity to fatigue and external disturbances could be reduced by additions to the feedforward control scheme. For example, voluntary wrist extension (either by weak residual control in C6 injury or by voluntary tendon transfer in C5 injury) should be able to decrease errors in wrist angle. Also, closed-loop wrist and hand grasp feedback should decrease errors between the actual and desired grasp and wrist parameters; however, sensors for grasp and wrist outputs will increase the complexity of the system.

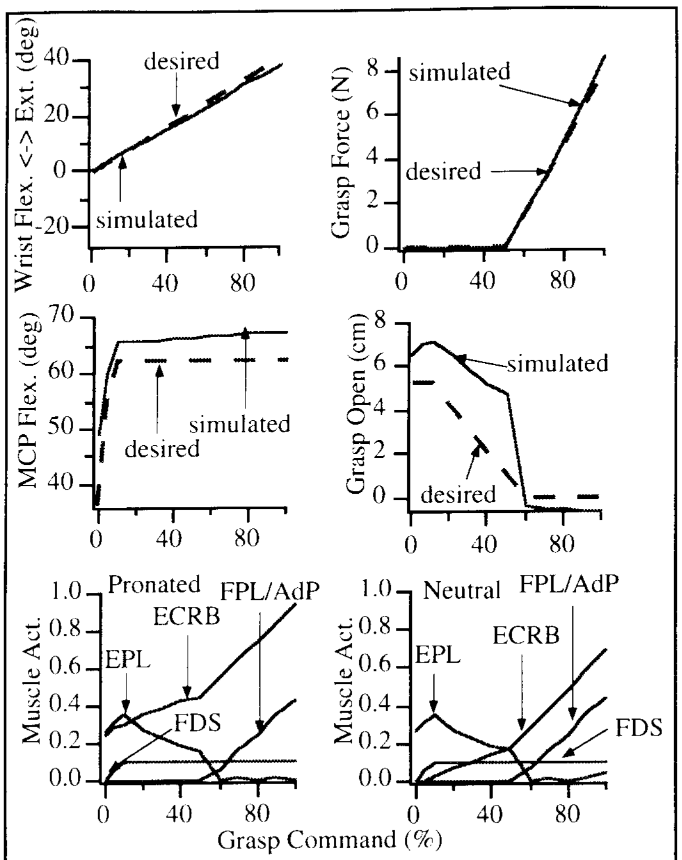

Fig. 2.b.iv.4. Input/output properties for tenodesis grasp during arm pronation; arm orientation an input to wrist module.

CONCLUSION

The feedforward controller was successful in learning the predictable interaction between hand grasp and wrist control, as well as compensate for the effect of gravity on wrist angle. Unpredictable disturbances introduced by grasping tasks, (e.g. muscle fatigue and external moments at the wrist) might generate significant errors between the desired and actual grasp and wrist parameters. Depending on the changes in the grasp and wrist parameters, though, the grasping task might still be successfully completed. Voluntary effort, and the addition of feedback control are some ways to compensate for the unpredictable disturbances. With these possible additions to the feedforward controller, integrated wrist and hand control should be possible in the neuroprosthesis, resulting in a more functional grasp for tetraplegics, and freedom from orthoses.

Plans for next quarter

We will work to complete the simulation phase of this work, and to plan experimental verification of the results with regard to the use of a feedforward controller.

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